

Determination of subject-specific muscle fatigue rates under static fatiguing operations

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Abstract

Cumulative local muscle fatigue may lead to potential musculoskeletal disorder (MSD) risks, and subject-specific muscle fatigability needs to be considered to reduce potential MSD risks. This study was conducted to determine local muscle fatigue rate at shoulder joint level based on an exponential function derived from a muscle fatigue model. Forty male subjects participated in a fatiguing operation under a static posture with a range of relative force levels (14% - 33%). Remaining maximum muscle strengths were measured after different fatiguing sessions. The time course of strength decline was fitted to the exponential function. Subject-specific fatigue rates of shoulder joint moment strength were determined. Good correspondence ($R^2 > 0.8$) was found in the regression of the majority (35 out of 40 subjects). Substantial inter-individual variability in fatigue rate was found and discussed.

Key words: static muscular strength, joint strength decline, muscle fatigue rate, subject-specific fatigue rate

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Practitioner summary

Different workers have different muscle fatigue attributes. Determination of joint-level subject-specific muscle fatigue rates can facilitate physical task assignment, work/rest scheduling, MSD prevention, and worker training and selection.

R2Q1

1. Introduction

Human intervention is often involved in occupational activities, especially in material handling, assembly, and maintenance tasks (Melhorn et al., 2001a,b; Kumar, 2001). In those activities, the operator needs sufficient muscle strength to meet force requirement for operating equipment or sustaining external loads. Insufficient strength can lead to overexertion of the musculoskeletal system and to consequent injuries (Armstrong et al., 1993; Chaffin et al., 1999).

R1Q1

A decrease in muscle strength is often experienced in a physical operation under a sub-maximal force, either in a continuous way or in an intermittent way (Wood et al., 1997; Yassierli and Nussbaum, 2009). This decrease in maximum force output results from different sources, such as muscle fatigue, musculoskeletal disorders, lack of motivation, etc. Among those sources, muscle fatigue is one of the most prevalent reasons and is defined as “any exercise-induced reduction in the capacity to generate force or power output” (Vøllestad, 1997). Muscle fatigue exposes operator to more risks of overexertion, and cumulative muscle fatigue may result in musculoskeletal disorders (MSDs) (Armstrong et al., 1993; Chaffin et al., 1999).

R1Q2

Fatigue progression is closely dependent on task assignment and subject-specific fatigue attributes. Different task parameters (load, duration of exertion, posture and

motion, etc.) lead to different fatigue progressions in physical operations ([Chaffin, 2009](#); [Yassierli and Nussbaum, 2009](#); [Enoka, 2012](#)). Individual physical attributes (e.g., strength, fatigue rates, recovery rates, etc.) can influence the fatigue progression as well. It is believed that fatigue attributes differentiate from each other among operators ([Yassierli et al., 2007](#); [Yassierli and Nussbaum, 2009](#); [Avin et al., 2010](#); [Avin and Law, 2011](#)). Determination of subject-specific fatigue attributes is of interest and of importance for physical work design ([Chaffin, 2009](#)).

Muscle fatigue progression has been studied mainly from two different approaches. One approach is maximum endurance time (MET) approach. MET can assess the ability to resist fatigue by measuring the maximal duration while exerting a force at a specific level until failure. A large amount of effort has been contributed to developing MET models for different muscle groups under different static working conditions ([Rohmert, 1960, 1973](#); [Rohmert et al., 1986](#); [Bishu et al., 1995](#); [Kanemura et al., 1999](#); [Mathiassen and Ahsberg, 1999](#); [Garg et al., 2002](#); [Law and Avin, 2010](#)). Although the MET models can predict the maximum endurance time under a given relative force level, the decrease in the muscular strength cannot be predicted directly by MET models. Moreover, due to the nature of the formation in those MET models from group data, it is difficult to determine subject-specific fatigue attributes.

Another approach to characterise muscle fatigue progression is to develop muscle fatigue models, and hence to predict the strength decline directly. Some work ([Giat et al., 1993](#); [Ding et al., 2000](#)) contributed to complex physiological muscle fatigue models. Those models are able to describe the muscle fatigue progression precisely for a single muscle. However, they are too complex for industrial application due to the difficulty of identifying a great number of parameters in the model.

Some researchers established some fatigue models by conducting fatiguing

tasks (Deeb et al., 1992; Sogaard et al., 2006; Roman-Liu et al., 2004, 2005; Iridiastadi and Nussbaum, 2006). Among those models, exponential declines in muscular strength are found (Deeb et al., 1992; Roman-Liu et al., 2004; Yassierli et al., 2007). However, the fitting parameters in those exponential functions could not implicate more information about fatigue attributes of each subject. R2Q9

Some other researchers (Liu et al., 2002; Ma et al., 2009; Xia and Frey Law, 2008) have tried other models to describe muscle fatigue progression. Xia and Frey Law (2008) proposed a three-compartment muscle fatigue model based on muscle motor units model in Liu et al. (2002), and they have run simulation to demonstrate fatigue progression under a variety of loading conditions. In this model, fatigue and recovery attributes of different types of muscle fibers were assigned with different values in the simulation. However, the lack of validation limits the application of this model. R1Q3

Ma et al. (2009) proposed a muscle fatigue model to describe muscle fatigue progression from a macro perspective. In this model, task parameters and muscle fatigue rate are combined together to understand the fatigue caused by tasks and fatigue attributes. Ma et al. (2011) developed an approach to determine fatigue resistances of different muscle groups using this fatigue model. Twenty-four MET models (El ahrache et al., 2006) for different muscle groups can be effectively fitted and explained by this approach. We suggest that this muscle fatigue model is capable of assessing fatigue progression of a muscle group in static cases. Moreover, we found that the muscle fatigue progression of each subject under static cases can be predicted in the form of an exponential function derived from the fatigue model, and one important factor (fatigue rate) in this model emerges to represent subject-specific muscle fatigue attribute. R2Q10

Regarding the subject-specific fatigability, some other measures were used to assess muscle fatigability, such as endurance time, EMG power spectrum (Median R1Q0

frequency (MF) and Median Power Frequency (MPF)), Mean Arterial Pressure (MAP) and so on (Clark et al., 2003; Hunter et al., 2004, 2005; Yoon et al., 2007; Frey Law and Avin, 2010; Côté, 2012). However, as pointed out by Vøllestad (1997), the greatest limitation is that those measures are indirect to measure muscle fatigue. Therefore, we chose to use the fatigue rate in Ma et al. (2011) to represent inter-individual difference in fatigue progression to beyond those limitations.

We conducted this study to verify whether the fatigue progression under a static operation can be well fitted by a specific exponential function derived from the muscle fatigue model and to check whether the fitting parameter (fatigue rate) could represent subject-specific fatigue attributes among different subjects. This paper is organised as follows: Section 2 describes the theoretical approach to determine subject-specific fatigue rate based on a muscle fatigue model. Section 3 presents materials, methods, and experiment procedure in this study. Section 4 and Section 5 show results and provide discussion.

R1Q4

R2Q11

R2Q12,

R1Q17

2. Subject-specific fatigue rate determination

The purpose of this study was to determine subject-specific muscle group fatigue attributes by analysing muscle fatigue progression based on a theoretical muscle fatigue model.

Ma et al. (2009) proposed a muscle fatigue model in the form of a differential equation (Eq. 1). The muscle fatigue model describes the change of the maximum remaining strength over time. Related parameters and their descriptions are given in Table 1. In this model, the fatigue rate (k) is a parameter to indicate the relative speed of strength decline within a muscle.

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R2Q13

R2Q14

$$\frac{dF_{rem}(t)}{dt} = -k \frac{F_{rem}(t)}{MVC} F_{load}(t) \quad (1)$$

[Table 1 about here.]

In a static muscular operation, $F_{load}(t)$ keeps constant, and the reduction of the muscular strength can be further predicted by Eq. 2. This equation describes the muscle fatigue progression in the form of an exponential function. Three parameters (F_{max} , F_{load} , and k) act upon the fatigue progression under a static operation. In general, F_{load} is determined by the task design, and it can be measured or calculated via force analysis, and F_{max} and F_{rem} can be measured to unfold the muscle fatigue progression. The fatigue rate k is task independent and it is influenced by several factors (e.g., muscle fiber type composition, age, and gender) (Ma et al., 2011).

R1Q7

R2Q13

R1Q12

$$\frac{F_{rem}(t)}{F_{max}} = e^{-k f_{MVC} t} \quad (2)$$

R1Q8

According to the definition of muscle fatigue, muscle fatigue progression can also be described by measuring the maximum remaining muscle strengths over time during a fatiguing operation. If the same muscle progression can be depicted using both ways, it will suggest the parameter k could be determined using the muscle fatigue model. Therefore, it is essential to verify whether the fatigue progression of each subject under a static fatiguing operation follows an exponential function in the form of Eq. 2 with a high coefficient of determination R^2 .

R1Q9,

R1Q10,

R1Q11,R2Q6

Suppose that we have already a set of real measurements for a given static operation, where F_{t_i} indicates the maximum remaining strength F_{rem} at time instant t_i . At the beginning of a physical task, the subject is supposed having no muscle fatigue. Therefore, the $F_{t=0}$ can be treated as the maximum voluntary contraction F_{max} . Equation 2 can be further transformed into Eq. 3.

$$\frac{\ln\left(\frac{F_{t_i}}{MVC}\right)}{f_{MVC}} = -k t_i \quad (3)$$

Since f_{load} and MVC are measured and/or known, fatigue rate k can be further determined by linear regression. A high goodness of fit between maximum remaining strengths and the exponential function would suggest the usefulness of the fatigue rate. The goodness of fit is assessed by the R^2 value in a linear regression without an intercept.

3. Materials and Methods

3.1. Subjects

Since the focus of this study is on manufacturing and assembly and the majority of the operators are male workers, 40 right-handed male industrial workers participated in the experiment after signing a written informed consent. The age, stature, body mass, upper limb anthropometry data, and body mass index (BMI) were recorded or measured upon arrival at the laboratory (see Table 2). Participation was limited to individuals with no previous history of upper limb problems. Ethical approval for this study was obtained from the human research ethical advisory committee of Tsinghua University.

[Table 2 about here.]

3.2. Task design

In this study, we used a typical overhead drilling operation under laboratory conditions to measure muscle fatigue progression at shoulder joint level (see Fig. 1). This task was simplified from a real drilling operation from the program of the European Aeronautic Defence and Space (EADS). This operation was selected as a

typical task because there are a few ergonomics problems (Melhorn et al., 2001a). A heavy external load demands great physical strength to hold a machine and maintain the operation for a certain period, and local muscle fatigue occurs rapidly in upper limb and lower back. MSD risks can be increased by force overexertion and long-lasting vibration while drilling.

R2Q15

The magnitude of the external load and the duration of the operation are two key factors to simulate the real situation. The relative load needs to be adequate so that subjects can experience fatigue and can endure the operation for a certain period. In this case, according to the strength model in Chaffin et al. (1999) and the MET models in El ahrache et al. (2006), a subject must apply a drilling force of 25 N and hold a drilling machine with a mass of 2.5 kg. The drilling force is only applied along the drilling direction towards the subject. The estimated moment generated by the external load (including the weight of the arm) is about 33% of the shoulder joint flexion strength of a 50th percentile male and the endurance time under this load is estimated around 4 minutes.

[Figure 1 about here.]

3.3. Measures

In this study, we used shoulder joint moment strength to describe fatigue progression and measured the maximum force output in the drilling direction to estimate shoulder joint moment strength (see Fig. 2).

R1Q5

We assumed that the measured force was determined by joint moment strength of the right upper limb. Shoulder joint and elbow joint have similar strength profiles according to the joint moment strength models (Chaffin et al., 1999), and shoulder joint has higher fatigability in MET models than elbow joint (Frey Law and Avin, 2010). Furthermore, it was obvious that shoulder joint was charged with a much

larger moment load than elbow joint in this drilling case. Therefore, the bottleneck for the output strength was shoulder joint.

The moment load in shoulder joint can be approximately estimated by Eq. 4 (see Fig. 2). The mass and the centre of gravity of each body segment were estimated from the anthropometry database (Chaffin et al., 1999).

$$\begin{aligned}\Gamma_{load} = & \left(\frac{\mathbf{s} - \mathbf{e}}{2} \right) \times \mathbf{G}_u + \left(\frac{\mathbf{w} + \mathbf{e}}{2} - \mathbf{s} \right) \times \mathbf{G}_f \\ & + \left(\frac{\mathbf{d} + \mathbf{w}}{2} - \mathbf{s} \right) \times \mathbf{G}_m + (\mathbf{d} - \mathbf{s}) \times \mathbf{F}_d\end{aligned}\quad (4)$$

where \mathbf{s} , \mathbf{e} , \mathbf{w} , and \mathbf{d} represent the coordinates of the positioning sensors attached to the shoulder (S), elbow (E), wrist (W), and drilling contact point (D), respectively.

In our experiment, since the subject's arm is strictly limited within the sagittal plane, we just measured the force and calculated the torque within this plane.

R1Q16

[Figure 2 about here.]

Since we use joint moment strength, the fatigue model in Eq. 1 can be changed to Eq. 5 by replacing all of the force terms with joint moment terms.

$$\frac{d\Gamma_{rem}(t)}{dt} = -k \frac{\Gamma_{load}(t)}{\Gamma_{max}} \Gamma_{rem}(t) \quad (5)$$

Under this simplified case, Γ_{load} can be determined by force analysis, and f_{MVC} can be calculated from data analysis by normalizing the Γ_{load} over Γ_{max} . Γ_{t_i} is a joint maximum remaining strength, and it can be estimated by measuring the maximum remaining force F_{t_i} in the drilling direction.

3.4. Material

In the experiment, we want to measure the muscular strength in the drilling direction and to estimate the joint moment strength around the shoulder joint. Therefore, force measurement and motion capture devices were used (see Figure 1).

We used a dynamometer to measure the drilling force in the drilling direction (see Figure 1). The dynamometer measures the pressing force perpendicular to the load cell surface with a measurement range upto 300 N and a precision of 1 N .

R1Q13

We use the magnetic motion capture device FASTRAK® (POLHEMUS Inc.) to capture the upper limb posture in the experiment. As shown in Figure 1, we attached four positioning sensors to the key joints of upper limb and the drilling machine. We captured the Cartesian coordinates of the shoulder, the elbow, the wrist, and the contact point between the drilling machine and the work piece. The tracking device runs at 30 Hz per sensor and has a static position accuracy of 1 mm . We used the recorded coordinates of each tracker to reconstruct the posture of the worker in post-experiment analysis.

We provided the drilling force with a wooden beam with a mass of 10 kg . We used wooden material to avoid magnetic distortions caused by ferrous material and to ensure motion capture accuracy. We suspended the wooden beam with an inclination angle between the beam and the horizontal line of 14.5° . During operation, the subject had to push the beam against the force measurement device and hold it for a certain period. According to the force analysis of the pendulum, a tangential force of 25 N was charged to the upper limb. Before each trial, we calibrated this external load to ensure that there was exactly a force of 25 N applied in the drilling direction. We provided the weight of the drilling machine with a drilling tool made from concrete with a mass of 2.5 kg .

3.5. Experiment Procedure

Each subject had to complete ten sessions: one MVC session and nine fatiguing sessions.

In the MVC session, maximum voluntary contraction (*MVC*) was determined as the greatest exerted force in the drilling direction over three trials. In each trial,

we verbally encouraged subjects to maintain the maximum force peak for three to five seconds. The measured *MVC* was also denoted as F_0 to represent the subject's initial maximum strength at the beginning of the operation. Between each trial, subjects were asked to take at least a 5-minute rest until self-reported full recovery (Chaffin et al., 1999).

There were nine fatiguing sessions with different time intervals (15, 30, 45, 60, 75, 90, 120, 150, and 180 seconds). The sequence to complete those nine sessions was randomly assigned for each subject. In each fatiguing session, subject was asked to hold the constant external load for the time interval t_i (e.g., 30 sec). After that, the remaining muscle strength F_{t_i} (e.g., F_{30}) was measured by asking the subject to exert the maximal voluntary strength with a force peak from three to five seconds. After the measurement, subjects took a rest for at least five minutes or even longer until self-reported total recovery.

After the recovery, the subject was asked randomly to **conduct a MVC trial**. Full recovery would be recognized if the measured maximum strength in this trial was more than 95% of the MVC. Otherwise, the subject would be asked to take longer break until full recovery. Once subject reported that he could not sustain the operation within the session, experiment would be stopped immediately to avoid injuries to subject.

Within each session, subject was seated upright, and right shoulder was fixed to a shoulder support against the wall to restrict the movement of shoulder and to decrease the engagement of lower back. Left upper limb was free, and right upper limb was limited in the sagittal plane by position constraints. The position constraints provided posture references to subject to maintain the initial posture as well as possible, but provided no support to upper limb. The seated height and location was adjusted according to subjects height and upper limb length to reduce variability among the different subjects.

3.6. Data Analysis

The objective of this analysis was twofold.

R2Q16

1. to test if the fatigue progression of each subject in shoulder joint maximum strength can be well fitted by the exponential function derived from the muscle fatigue model or not;
2. to analyse the relationship between muscle fatigue rate and joint moment strength.

R2Q3

For the first objective, we fitted muscle fatigue progression of each subject with the exponential function (Eq. 3). The coefficient of determination of each fitting was recorded for each subject and analysed. For the second objective, we selected two groups of subjects to assess the relationship of joint moment strength and joint fatigue rate, since muscles engaged in the action mainly determine maximum joint strength and we assumed that determinant muscle-related factors for muscle strength could probably act effects on muscle fatigue rate as well. One group (Group A) is the subjects with 10 highest joint moment strengths; another group is the subjects with 10 lowest joint moment strengths. Besides joint strength, some other measures (e.g., BMI, age) may also influence fatigue rate. Correlations between fatigue rate and other measures were also statistically analysed. We used SPSS to do all the statistical analysis and fitting.

R1Q12,

R1Q17,

R1Q19

4. Results

4.1. Fatigue progression

Joint moments of each subject were normalized over the estimated maximum moment strength. Then the normalized values were fitted using Eq. 3 to calculate the fitting coefficient R^2 and to determine the fatigue rate. The statistical results of

R^2 of the regression and the fatigue rate k were listed in Table 3, and the histograms of R^2 and k were shown in Fig. 4 and Fig. 5.

35 out of 40 subjects had a high coefficient of determination R^2 over 0.8 in joint moment regression. Four out of the other five subjects had a fair coefficient R^2 over 0.63, and only one of the five subjects had a very poor R^2 (0.23).

R2Q4

[Table 3 about here.]

[Figure 3 about here.]

5. Discussion

5.1. Muscle fatigue progression

In this study, we found that the fatigue progression at shoulder joint among most of the subjects (35/40) can be well fitted ($R^2 > 0.8$) by the muscle fatigue model. Five out of 40 subjects were found with low R^2 coefficients.

R2Q6

There are some reasons leading to those relatively poor fittings. First, the motivation and the attitude of the subject during the experiment could influence the result. Second, **even though** the posture of the arm was strictly constrained in the sagittal plane, subjects could still have a certain degree of mobility. The willingness to maintain the posture may influence the muscle recruitment strategy, muscle coordination, and the posture during the experiment. **Third, weak muscular strength** could probably lead to poor fitting performance indirectly. The subject with a $R^2 = 0.23$ had the second lowest MVC among the 40 subjects. Lower muscle strength means relatively higher physical workload during the experiment and higher demand to maintain the posture, and hence the static operation would be more possibly adversely influenced due to the unwillingness to maintain the posture.

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R2Q20

R2Q7,

R2Q19

Fatigue may occur at any step along the pathway that is involved in muscle contraction (Berne et al., 2004). Both the metabolic factors within the muscle and the impairment of activation could contribute to the decline in muscle power output (Chaffin et al., 1999; Allen et al., 2008). In a physical operation, muscle fatigue progression could be influenced by physical task, motivation, and individual fatigue attributes. However, under static operation and effective verbal encouragement, the influences from motivation could be rather limited. Therefore, muscle fatigue progression was probably mainly caused by relative loads and subject-specific fatigue attributes in this study.

R1Q21

The fatigue model (Eq. 2) is formed from a macro perspective and can be explained based on motor units principle from a micro perspective (Ma et al., 2009). The product of relative load and fatigue rate determines the decline of muscle strength. According to muscle physiology, fatigue rate can be recognized as a parameter to represent the overall fatigue resistant performance of a muscle group at joint level under a specific task (Ma et al., 2011).

R1Q23

We selected this model to determine fatigue attribute for the following reasons: (1) in comparison to Deeb's model (Deeb et al., 1992), this model enables us to decouple relative load and subject-specific attribute; (2) muscle fatigue rate can be influenced by muscle composition, neuromuscular activation patterns, and coordination among single muscles, therefore the fatigue rate in this model could cover more effects of influencing factors than the fatigue rates of different types of muscle fibers in Xia and Frey Law (2008); (3) this model is less complex than the three-compartment model in Xia and Frey Law (2008), and it could be practical for industry application.

R1Q22

5.2. Subject-specific fatigue rate

We found that there are substantial differences among different subjects in fatigue rates at shoulder joint level. It suggests that the fatigue rate k can be used to characterise different fatigue attributes among subjects at shoulder joint level under this specific fatiguing condition.

The underlying mechanisms for those differences in fatigue rate are very complex. Physiologically, differences in fatigue rates are mainly caused by four factors: (1) muscle strength (muscle mass) and associated vascular occlusion, (2) substrate utilisation, (3) muscle composition, and (4) neuromuscular activation patterns (Hicks et al., 2001; Ma et al., 2011). At the same time, demographic parameters (age, gender) and their interactions can lead to changes in muscle composition as well (Mademli and Arampatzis, 2008; Yassierli and Nussbaum, 2009). In addition, personal working experience or physical exercises and living style (e.g., smoking) can also change the muscle strength and endurance via the adaptive response of muscle cells to regular external loads (Berne et al., 2004; Wüst et al., 2008). All those factors generate effects together on subject-specific fatigue attributes.

We found also that **fatigue rates are positively correlated to maximum joint moment strength in this study, even though the relative loads for the subjects with higher strength were lower.** Between-subject differences in the ratio of type I muscle fibers (slow twitch, more fatigue resistant) to type II muscle fibers (fast twitch, less fatigue resistant) might explain the differences in fatigue rates. Muscle strength depends strongly on muscle fiber size and muscle fiber composition (Fitts et al., 1991). Subjects in Group A and Group B did not have significant differences in BMI and age, which implicates that the strength differences were probably not mainly caused by muscle mass or muscle fiber size or age-related factors. It could be concluded that the strength differences were caused by different compositions

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R2Q17,

R2Q21

of muscle fiber types. Subjects with higher strengths could probably have a higher proportion of type II muscle fibers and lower proportion of type I muscle fibers. That leads to higher joint moment strength and faster fatigability in the muscle.

We did not find significant correlation between fatigue rate and age and between fatigue rate and BMI. Regarding the age effect, we did not control our subjects strictly to two age groups. The subjects in this experiment were in their young age or middle age, which might not enough to reveal the aging effect. Regarding the BMI, most of the subjects were in normal weight and overweight group. Only a few subjects belong to Class I obesity or underweight category.

5.3. Posture change

Although posture references were provided to avoid mismatches in different test trials, it was still very difficult for subjects to maintain the purely static posture during the operation. Small changes occurred in the experiment, but those changes did not generate excessive variation in joint strength. In our case, the variation of the maximum joint moment strength is no more than 3% relative to the maximum strength under the initial posture according to the joint moment strength model (Chaffin et al., 1999). The change of the joint strength due to posture change might lead change of the relative strength. We checked the sensitivity of the change, and the changed maximum joint strength would lead to no more than 4% change of the relative strength ($4\% f_{MVC}$), which was acceptable in this case.

R1Q20

Several reasons may cause posture change in the experiment. Fatigue might be one of those reasons. Changes in the posture can be explained by a global posture control strategy, which includes decreasing the joint loads in the operation by moving the upper limb closer to the body; a similar finding has been reported by Fuller et al. (2008). However, that change would influence joint strength (Roman-Liu and Tokarski, 2005; Anderson et al., 2007). Besides fatigue, there were still other error sources

leading to the change of the posture. First, the actual posture was determined by the anthropometry of different subjects. Different arm lengths could cause potential differences in elbow flexion and shoulder flexion. Second, the posture was calculated from the position sensors attached to the key joints. Each subject might have different sensor configurations, which might lead to calculation errors. Third, there might be differences among the postures that each subject took in different fatiguing sessions.

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5.4. Limitations

R1Q24,

There are several limitations in this study. First, the focus of the present study is on the fatigue effect in static industrial operations in a continuous working process. Recovery effect is not taken into consideration in this study. Second, this study was conducted under a simplified overhead drilling operation, and the conclusion drawn from this study has a strong task dependency. A simplified overhead drilling operation decreases the reliability of applying the findings into industry. Some other MSD causes, such as vibration (Kattel et al., 1999) were neglected from this study. Third, the force analysis in this study is available only for a static case. In a real operation, the motion involved in the operation could result in a different dynamic workload. Moreover, only fatigue with the relative force falling from 14% to 33% (Mean=24.3%, SD=4.4%) of the specific job operation was tested, so the result that was obtained is available only for similar physical operations. Last but not least, the fatigue progression was measured under static isometric contraction, and the results could not be extended for dynamic or intermittent fatiguing tasks.

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R1Q20

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R2Q22,

R2Q23

6. Conclusions and perspectives

This paper provides an experimental approach to determine subject-specific fatigue rate at shoulder joint level. Fatigue progression in a simplified static drilling

operation was measured and analysed using an exponential muscle fatigue model. The muscle fatigue progression in joint moment strength could be well fitted by the fatigue model ($R^2 > 0.8$). This result suggests that the muscle fatigue model could be used to describe fatigue progression for industrial operations within the range of 14% -33% of the relative submaximal level under static cases. Different fatigue rates among subjects could be used to characterise the individual fatigue attributes under the same workload. Determination of subject-specific fatigue rates could be useful for physical task assignment, worker training, worker selection and work design.

Since fatigue rate is important and it could be influenced by a number of factors, further study would be necessary to find the effects of these influencing factors (Côté, 2012). Gender difference, age difference, and joint difference in fatigue rates could be investigated. Static continuous and dynamic intermittent tasks could be investigated under different relative load levels. More strict posture control is necessary to eliminate effects of posture change.

R2Q8

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R2Q24

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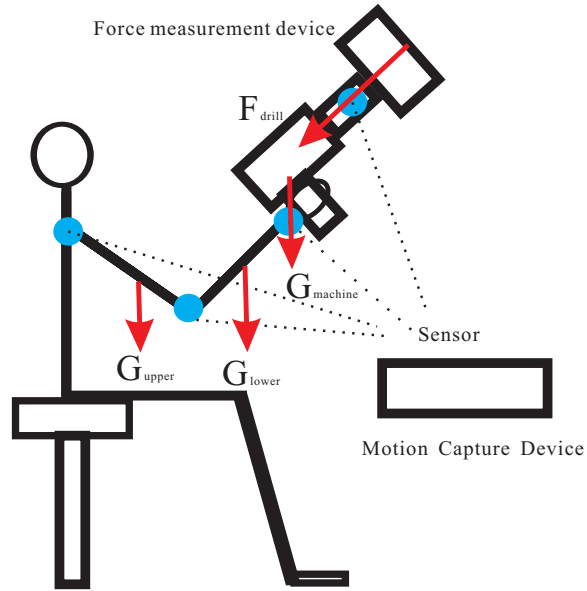


Figure 1: Seated static posture in the experiment and materials used in the experiment. F_{drill} : drilling force; $G_{machine}$: the weight of the drilling machine; G_{upper} : the weight of the upper arm; G_{lower} : the weight of the lower arm

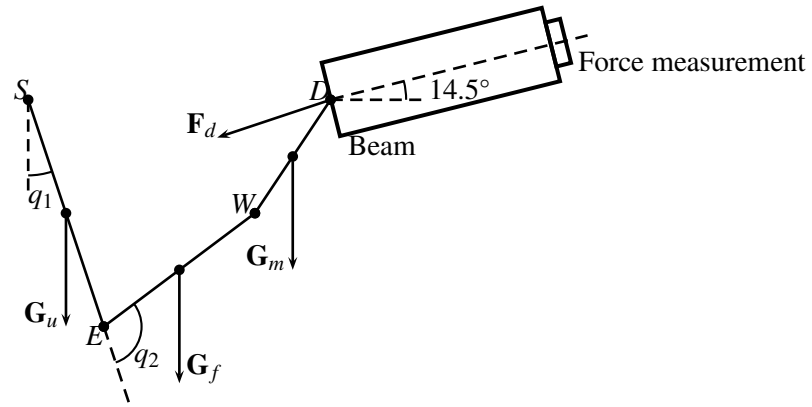


Figure 2: Force schema in the drilling operation. S: shoulder; E: elbow; W: wrist; D: drilling point. \mathbf{F}_d : drilling force applied to the upper limb; \mathbf{G}_m : weight of the drilling machine; \mathbf{G}_u : weight of the upper arm; \mathbf{G}_f : weight of the forearm; q_1 : flexion of the upper arm; and q_2 : flexion of the elbow

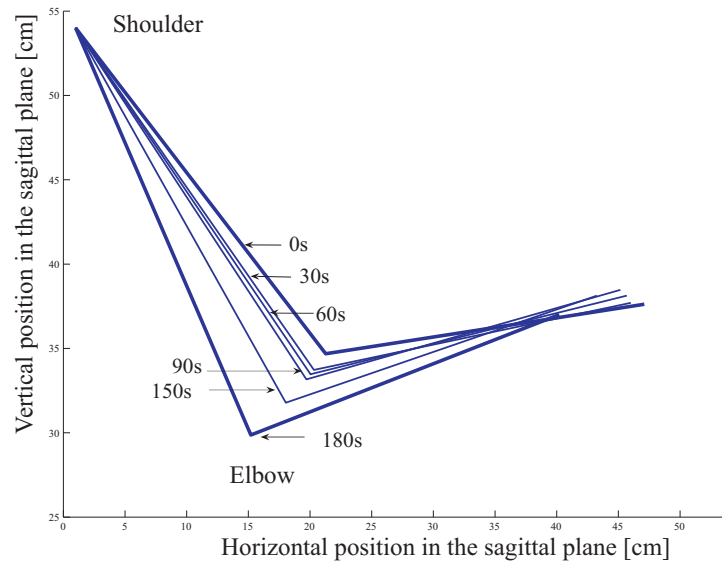


Figure 3: Posture change during the drilling operation (mean values across participants)

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Table 1: Parameters in the dynamic fatigue model

Item	Unit	Description
MVC or F_{max}	N	Maximum voluntary muscle strength under nonfatigued state
$F_{rem}(t)$	N	Maximum voluntary remaining muscle strength at time t
$F_{load}(t)$	N	External load that the muscle needs to bear
k	min^{-1}	Fatigue rate
$\%MVC$		Percentage of the voluntary maximum contraction
f_{MVC}		$\%MVC/100$, $f_{MVC} = \frac{F_{load}}{MVC}$.

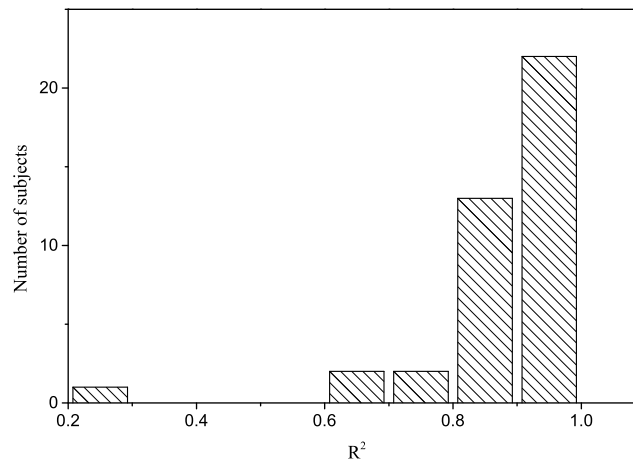
Table 2: Subject physical characteristics

Characteristic	Mean	Standard Deviation (SD)	Maximum	Minimum
Age (year)	41.2	11.4	58	19
Height (cm)	171.2	5.1	183.0	160.0
Mass (kg)	70.2	10.4	95.0	50.0
Upper limb (cm)	23.6	3.0	31.0	16.0
Lower limb (cm)	25.6	1.8	29.0	22.0
BMI	23.9	3.35	31.1	18.7

Table 3: Statistical analysis of fatigue rate k

Item	Mean	SD	Minimum	Maximum
Joint moment strength (Nm)	45.1	7.4	67.4	32.1
k	1.02	0.49	0.37	2.29
R^2	0.87	0.14	0.23	0.99

R2Q18

Figure 4: Histogram of coefficient of determination R^2

R1Q18

R1Q18

6.1. Relationship between fatigue rate and joint maximum strength

A pair-wise correlation matrix was determined between joint moment fatigue rate, joint moment strength, age and BMI. The results were shown in Table 4. It was found that joint moment strength is strongly correlated with fatigue rate ($p < 0.05$), while no strong correlations were found in the pair of fatigue rate and BMI and the pair of fatigue rate and age.

Table 4: Correlation matrix for study variables. (* $p < 0.05$)

	Fatigue rate	BMI	Joint moment strength	Age
Fatigue rate	1	-0.09	0.616*	0.033
BMI		1	0.09	0.40*
Joint moment strength			1	0.072
Age				1

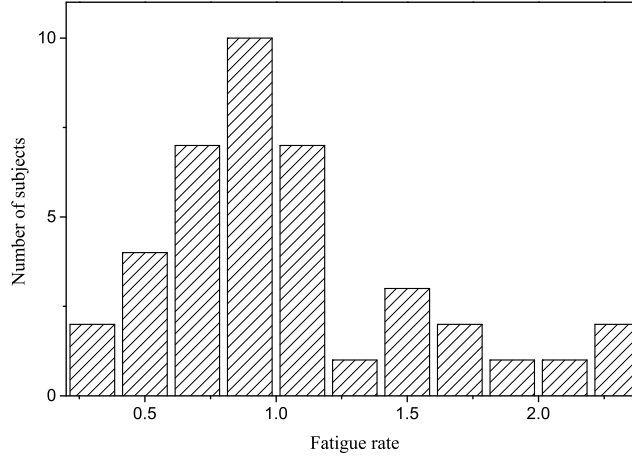


Figure 5: Histogram of fatigue rate at shoulder joint

No significant differences were found between two groups in age (Group A: 42.9 (SD=7.4); Group B: 39.1 (SD=15.4), $p = 0.49$) and BMI (Group A: 24.9 (SD=2.4); Group B: 25.2 (SD=4.2) $p = 0.78$). Significant differences ($p = 0.00$) were found in joint maximum strength between Group A (mean=60.8 Nm (SD=4.7Nm)) and Group B (Mean=37.7 Nm (SD=3.3 Nm)) .

With use of t-test, Table 5 showed the difference of fatigue rates between different groups. The subjects with higher strength have significantly higher fatigue rate **even though** the relative load is smaller than the subjects with lower strength.

Group	Mean	SD	t	p -Value
k				
A	1.47	0.53	4.628	0.0001
B	0.64	0.20		

6.2. Posture change during the drilling operation

We calculated the posture of upper limb during the drilling operation from the motion data. Because the arm was constrained in the sagittal plane, only the flexion angles of shoulder joint and elbow joint were calculated to represent arm posture to eliminate influence from different limb lengths. The statistical results of elbow

flexion and shoulder flexion angles across participants were calculated and shown in Table 6. The posture change during the working process is shown in Figure 3. The changes in the posture followed the following tendency: the greater the fatigue was, the closer the upper limb was to the trunk. In this way, the moment produced by the mass of the upper limb around shoulder joint could be reduced.

Table 6: Posture change during the experiment (deg)

Time (sec)	0	15	30	45	60	75	90	120	150	180
Elbow										
Mean	50.1	53.1	55.1	55.1	57.5	59.9	59.9	64.2	66.7	75.5
SD	16.1	15.4	15.0	15.7	16.4	19.0	19.2	19.9	21.3	21.9
Shoulder										
Mean	46.4	44.5	43.6	44.2	42.8	42.1	41.9	39.7	37.5	30.5
SD	16.2	15.0	14.6	15.2	14.7	16.6	17.0	16.6	17.9	17.3